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(54) Abstract Title
NMR gradient coil with parallel conducting paths

(57) In order to allow strong magnetic field gradients to be created without applying large voltages of one kilovolt AC or more to a gradient coil such as may be used in magnetic resonance imaging and spectroscopy (MRIS), four identical coil windings A, B, C and D are disposed symmetrically in space relative to each other, each winding comprising four interwound spiral conductive paths 1, 2, 3 and 4 of different configurations. The individual windings are interconnected so as to form four separate circuits each of which spans all four windings and comprises a respective conductive path within each winding such that the four conductive paths within each circuit are of different configurations. For example the four circuits may consist of the following combinations of conductive paths: (A1 + B4 + C2 + D3), (A2 + B3 + C1 + D4), (A3 + B2 + C4 + D1) and (A4 + B1 + C3 + D2). The four circuits are connected together in parallel.

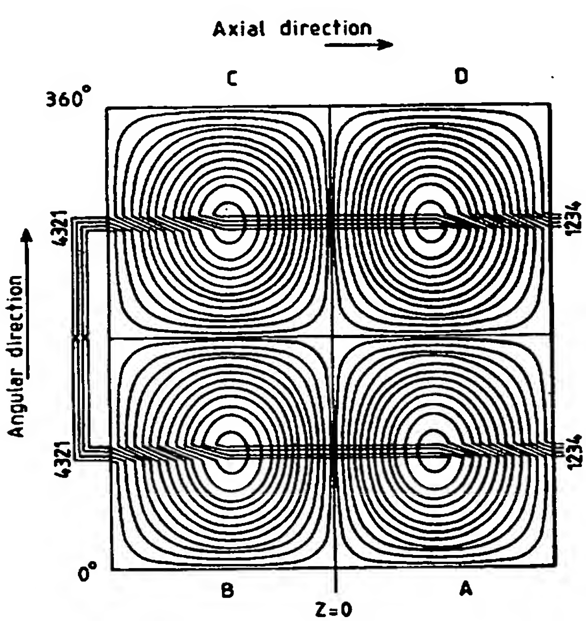

FIG 4

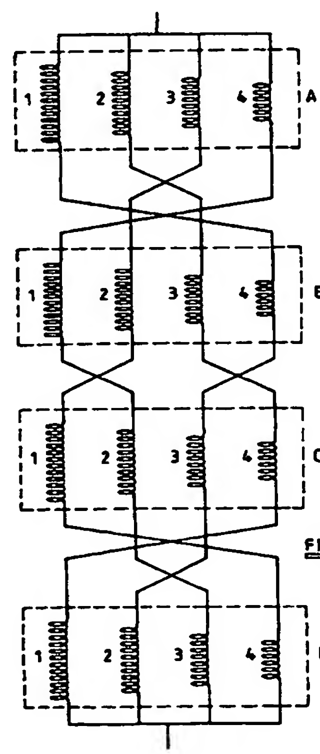

FIG 5

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At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

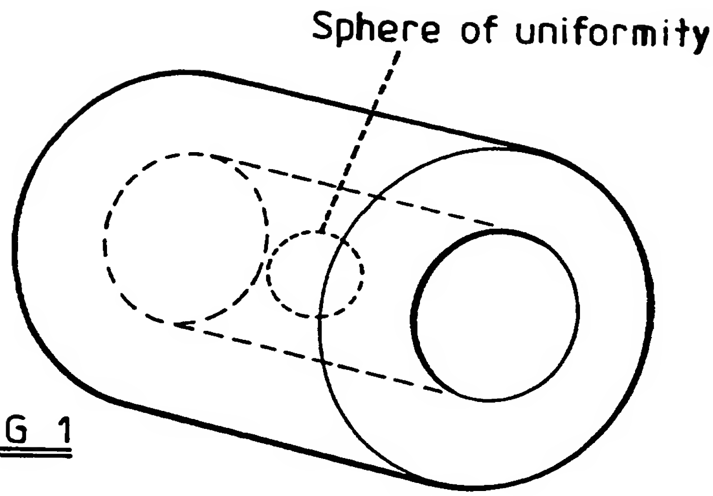


FIG 1

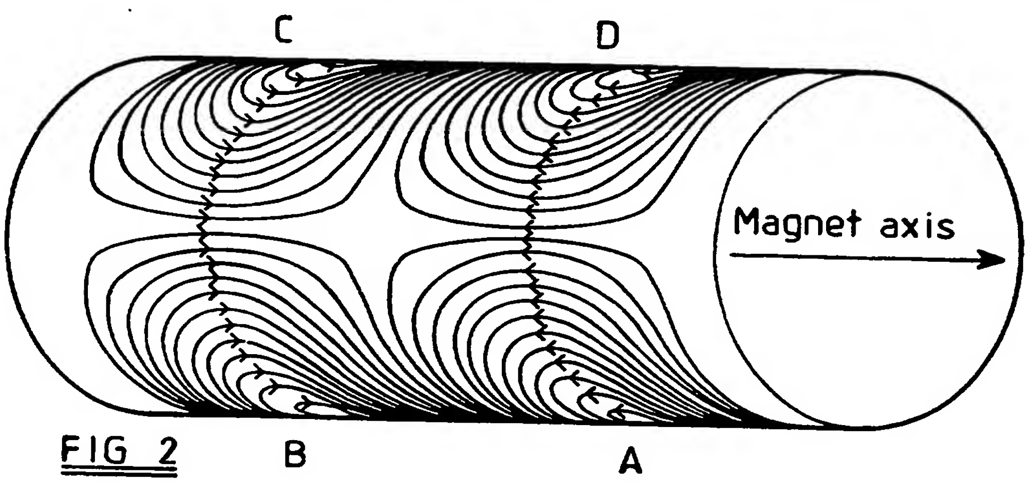


FIG 2

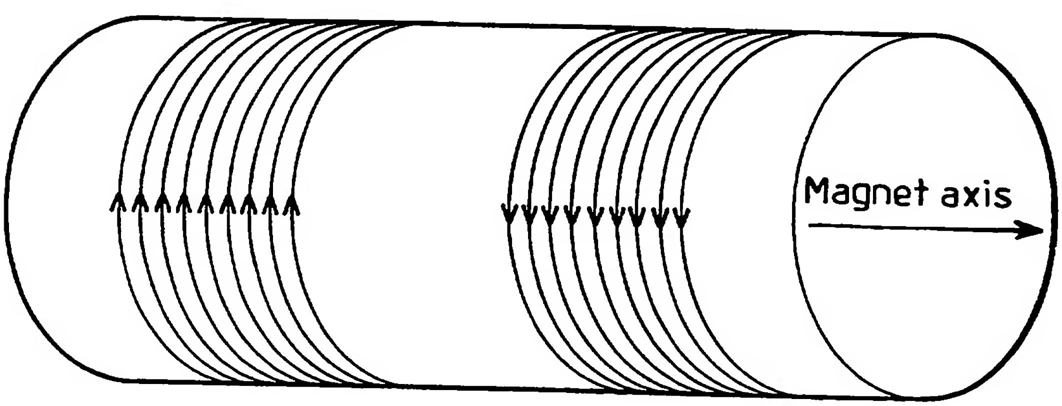
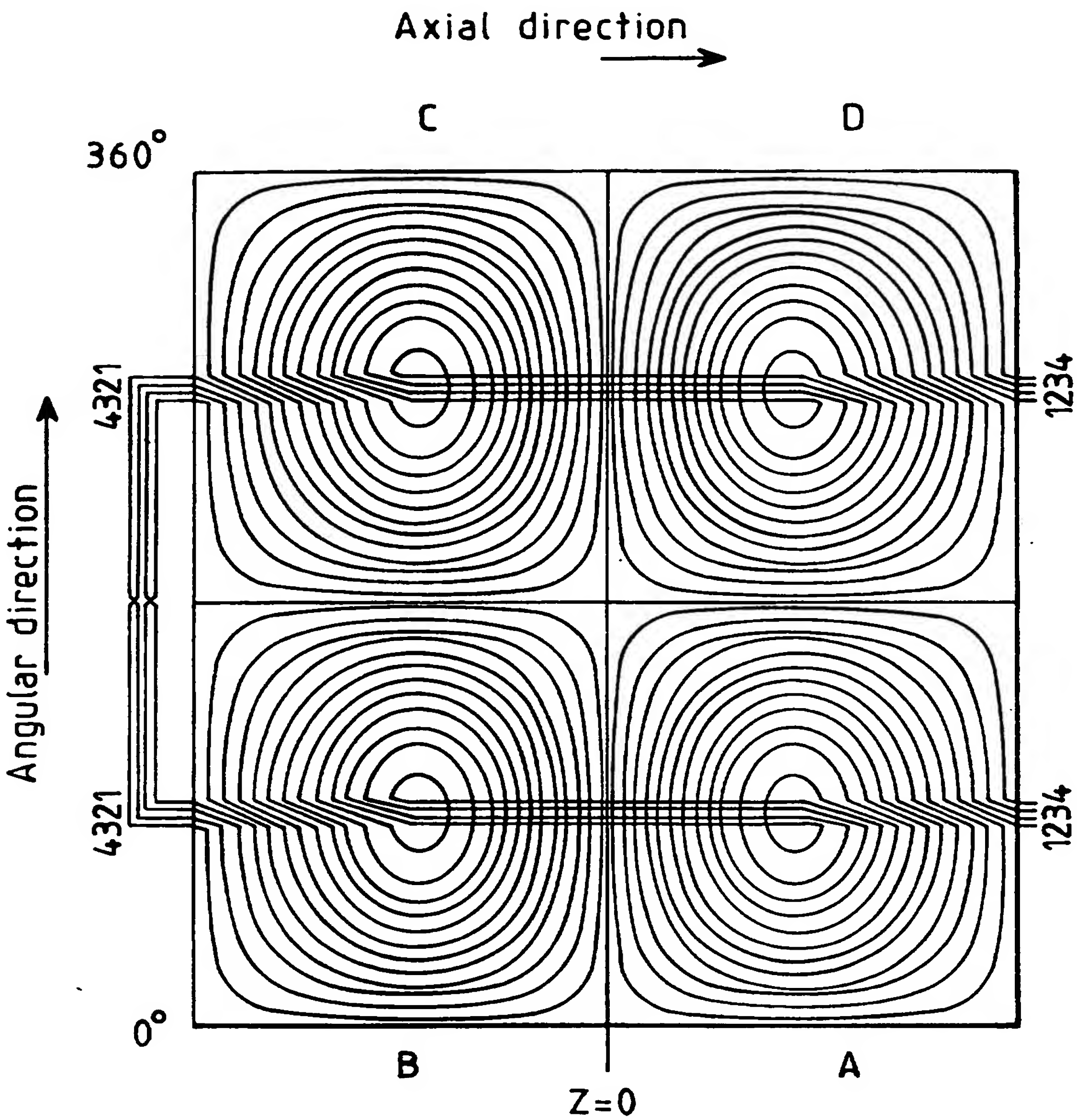


FIG 3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C
D
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4321
1234
Angular direction
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B
A
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FIG 4

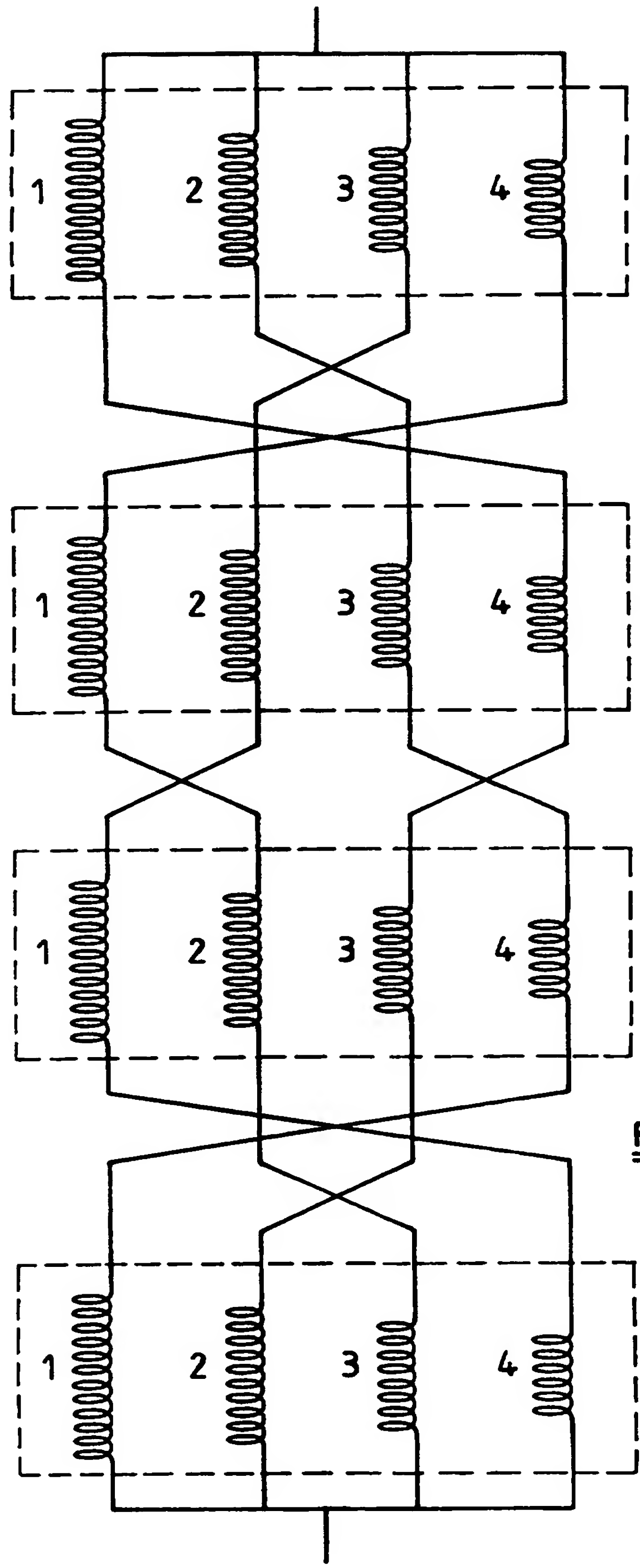

FIG 5

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ELECTROMAGNET APPARATUS

The present invention relates to electromagnet apparatus comprising gradient coils for MRIS (i.e. magnetic resonance imaging and spectroscopy). The present invention is particularly but not exclusively of relevance to clinical whole-body MRIS. Preferably, the invention concerns gradient coils having reduced AC loss (i.e. alternating current loss) characteristics.

MRIS is a method for obtaining information selectable from at least one of: spatial information, chemical information, physico-chemical information, and functional information from animate or inanimate subject matter. The essence of MRIS is to place the subject in a high, spatially uniform, static magnetic field, e.g. a magnetic field of at least 0.05 Tesla. Some nuclei of the subject are capable of precessing at a frequency characteristic of the nuclear species and directly proportional to the high, spatially uniform, static magnetic field. To cause such precession, an additional radio frequency magnetic field is applied for a suitable time. When that additional field is removed, the nuclei continue to precess for a period, typically milliseconds to seconds. During this period, a radio frequency signal can be detected from the subject, by placing a tuned coil nearby. From this detected signal, information about the subject can be deduced.

The problem arises of how to identify the location from which comes the signal to be detected, if all the nuclei are precessing at the same frequency and they are all being detected by a single tuned coil. This problem may be overcome by utilising magnetic coil windings (i.e. gradient windings), which modulate the high, spatially uniform, static magnetic field with a parallel or anti-parallel magnetic field, the magnitude of which varies with position. Such a further magnetic field is referred to as a gradient field. It is conventional to have three such gradient fields respectively proportional to each of the three cartesian axes, X, Y, and Z. Using these three gradient fields, the frequencies and phases of the detected signals can be encoded with spatial information. Techniques have been developed to obtain three dimensional spatial information by rapid, controlled, switching of the gradient fields.

The most common electromagnet geometry for MRIS is a superconducting solenoidal cylinder (i.e. first cylinder) having an axis of symmetry and a region of uniform

magnetic field at the centre of that cylinder. (Fig. 1 of the accompanying drawings) A full set of gradient windings for such a magnet comprises at least three coil windings respectively for the X,Y, and Z axes. By convention, the Z axis is parallel to the magnet's axis of symmetry, the X axis is horizontal across the magnet, and the Y axis is vertical relative to the magnet. An X gradient field may be generated by utilising a set of at least four X gradient coils A,B,C,D with appropriate current senses laid on a said first cylinder. (Fig. 2 of the accompanying drawings) The four gradient coils may be termed saddle coils. They have one or more planes of symmetry (three in the case of an X or Y gradient coil). The four gradient coils (saddles) may be connected in series. A Y gradient coil resembles an X gradient coil, rotated through 90° about the Z axis. A Z gradient coil may comprise two sets of circular windings, connected so that when current flows clockwise in one of those sets, the current flows anti-clockwise in the other set. X and Y gradient coils may be manufactured by cutting or etching a complex track in a sheet of electrically conductive material. To minimise heat dissipation, it is desirable to leave as much conductive material in the sheet as possible, resulting in a pattern having conductive tracks of variable widths. Z gradient coils may be manufactured from conductive strip or wire.

Further gradient windings (known as shield windings) may be located on at least one other cylinder, larger than said first cylinder. The purpose of shield windings is to confine within the shield windings any stray time-varying magnetic fields, so as to prevent interactions between X, Y, Z gradient coils and the magnet that generates the high, spatially uniform, static magnetic field.

There is an increasing demand for high strength magnetic field gradients with very short switching times - e.g. from 0 to 25 millitesla/meter (mT/m) in 100 microseconds (μs) in a clinical imager. The goal is to generate a particular distribution of magnetic fields in space (with a particular, fixed amount of magnetic energy) in a predetermined time. To do this, an appropriate distribution of electrical current must be provided in a gradient winding in the same time interval. The current distribution may be generated in various manners, e.g. by a coil winding having few turns, carrying a high current and at a low voltage, or by a coil winding with many turns, carrying a smaller current at a high voltage - see later below. If a coil winding is designed to operate at

high currents, moderate voltages are needed to switch it on (first case). If a coil winding is designed to operate at moderate currents, high voltages are needed to switch it on (second case). The instantaneous drive - power for gradient switching (Peak Volts x Peak Amps) may be the same in both cases.

The present invention allows strong magnetic field gradients to be created without applying large voltages of one kilovolt (kV) AC or more to a gradient coil.

According to the present invention, there is provided electromagnet apparatus for providing at least one magnetic field gradient, comprising:

a plurality of sets of conductors that are at least portions of respective coil windings, comprising first and second sets of said conductors, wherein said first and said second set each comprise the same plural number of respective conductors that are electrically isolated from each other within each said set and have respective occurences within that set, said second set being interconnected with said first set, said second set being in a predetermined geometrical relationship with said first set, such that said first and second sets are optionally symmetrically disposed in space, and such that the configurations of said conductors in said second set are optionally in a predetermined geometrical relationship with the configurations of said conductors in said first set; and wherein:

a said conductor of said first set is connected to a said conductor of said second set, those two conductors being constituted by one continuous conductive member or by at least two joined together conductive members, the occurrence of said conductor in said second set being distinguished from the occurrence in said first set of a conductor to which is connected said conductor in said second set.

Said first and second sets enable voltages of e.g. 500 volts AC to be applied to the electromagnet apparatus of the present invention, instead of large voltages of at least one k Volt AC. The applied voltages may be further reduced by increasing the number of said first and second sets. The first and second sets may have reduced AC loss characteristics.

In said electromagnet apparatus of the present invention, said plurality may comprise first and second said sets adapted and arranged for providing electromagnetic X field gradient(s). Said plurality may comprise first and second said sets adapted and arranged for providing electromagnetic Y field gradient(s). Said plurality may comprise

first and second said sets adapted and arranged for providing electromagnetic Z field gradient(s). Said plurality is preferably an even number, for example 4. Said conductors in said first set may be in a first configuration, and said conductors in said second set may be in a second configuration, such that in said first and second configurations, the outermost conductor of said second configuration communicates with the innermost conductor of said first configuration, and in corresponding manner the remaining conductor(s) of said second configuration communicate(s) with the remaining conductor(s) of said first configuration, and the innermost conductor of said second configuration communicates with the outermost conductor of said first configuration.

Said electromagnet apparatus of the present invention may comprise at least one further said first set and at least one further said second set, such that those further sets respectively constitute at least a third set of conductors and a fourth set of conductors, wherein said first and second sets and said third and fourth sets are at respective locations. Said third and fourth sets may be displaced from said first and second sets, the displacement optionally being relative to a predetermined axial direction (Fig. 4 of the accompanying drawings). The disposition of said third and fourth sets may result from at least one notional motion of translation of one or more of said third and fourth sets, and/or may result from at least one notional motion of rotation of one or more of said third and fourth sets. For example, said third and fourth sets may be axially separated from said first and second sets and optionally mirror said first and second sets (Fig. 4 of the accompanying drawings).

Said electromagnet apparatus of the present invention may be such that all said sets of conductors are adapted and arranged to provide a predetermined electromagnetic field in a predetermined space, which space may be located relative to a nuclear magnetic resonance (i.e. NMR) magnet. Said predetermined space may be located relative to an NMR detector coil. Preferably, said predetermined space is an NMR imaging region for at least one portion of a patient.

When an electromagnet coil is switched on or off rapidly, a phenomenon known as "skin effect" forces electric current to flow mainly in the surface of the conductor constituting that coil. Because current is only flowing in part of the conductor, the effective resistance of the conductor is increased. This effect is referred to as an AC loss

mechanism, and can be quantified by measuring a frequency-dependent component of resistance, known as the AC resistance. AC loss mechanisms in conventional gradient coils are comparable, in effect, to a form of viscous drag, which slows the switching-time and increases the heat dissipation in the assembly. This effect becomes significant when the width of the conductor becomes comparable with the "skin depth" of the material. For example, in pure copper at 1 kilohertz (kHz) and room temperature, the value of the skin depth is 2mm. AC losses become significant at 1kHz if the maximum track-width in a gradient coil exceeds 6mm. The skin effect may also create undesirable time-varying magnetic fields in the gradient's imaging volume, as currents re-distribute after a switching event.

The conventional way to minimise AC loss mechanisms in gradient coils is to choose a many-turn implementation, running at moderate current, and high or very high voltages. However, proofing the implementation's structure against very high voltages adds technical difficulty and cost. The high voltages also necessitate additional layers of dielectric material, which make it more difficult to extract heat from the structure. To eliminate conductor areas where the track-width of a gradient coil conductor exceeds a predetermined limit, one can, instead, make the coil windings of conductive strip or wire. The resistance of a wire-wound gradient coil is determined by its length, cross-section, and the properties of its material. The cross-section area of electrically conductive material of a wire-wound gradient coil is limited by the point at which the turns are most closely packed. Consequently there is considerable "dead space" on the winding surface, and the DC resistance is comparatively high. Another stratagem for controlling AC losses in a sheet implementation is to set an upper limit, typically 6 to 10 mm, on the track-width, and to cut away some conductor in areas where the limit is exceeded. However, this imposes a "dead-space" resistance penalty similar to that incurred by using wire. Moreover, this technique does not remove the requirement for many turns and high voltages.

Said electromagnetic apparatus of present invention provides a novel arrangement of windings which preserves many of the advantages of the high voltage, low current design, while working at lower voltages and higher currents.

A conventional gradient winding may comprise four identical sub-units (e.g. saddle coil windings) symmetrically disposed in space relative to each other. Each sub-unit consists of a single conducting path. The sub-units are connected in series to form a single circuit. In some examples of the present invention, each said sub-unit may comprise four separate, non-identical, distinguishable electrically conductive paths (e.g. 1,2,3,4 in Fig. 4 of the accompanying drawings). Each said path may be relatively narrow. Each said path may be termed a "lane". Individual lanes in different sub-units may be connected in series, to form (e.g.) four separate circuits, each spanning all four sub-units. Each said circuit may contain a plurality of respective distinguishable lanes. Preferably, in the present invention, there is overall symmetry of the assembly of sub-units, taken as a whole, such that there is no reason for current to flow preferentially in one circuit rather than another. If desired, in accordance with the present invention, the circuits may have ends connected together in parallel, but not elsewhere, to form a single circuit with low DC resistance and low AC loss characteristics.

The present invention will now be described by way of example with reference to the accompanying schematic drawings, in which:

Fig. 1 shows a conventional solenoidal magnet.

Fig. 2 shows a conventional X or Y gradient coil, with relative current sense.

Fig. 3 shows a conventional Z gradient coil, with relative current sense.

Fig. 4 shows one example of an unwrapped version of an X or Y gradient coil according to the present invention, corresponding to Fig. 2.

Fig. 5 shows circuitry corresponding to Fig. 4.

In one example, the present invention provides individual saddles constructed from electrically conductive sheet, but with multiple inter-wound spirals, rather than a single spiral. The spirals are not, in general, regular or identical. The distinguishable spirals on saddle A (Figs. 4,5) are A1,A2,A3,A4, etc.

When the saddles on a former (inner or outer) are interconnected, the individual spirals are kept separate, and a number of electrically distinct composite circuits are formed (Fig. 4 shows this example in "unwrapped" form). Each resultant composite circuit contains a spiral of each type; for example, if there are four saddles, A,B,C, and D (i.e. four sub-units), each containing four respective spirals, 1,2,3, and 4

(Fig. 5), i.e. four non-identical,distinguishable electrically conductive paths or lanes, then the four composite circuits might be:

(A1+B4+C2+D3)

(A2+B3+C1+D4)

(A3+B2+C4+D1)

(A4+B1+C3+D2)

A schematic representation of one interconnection scheme is shown in Fig. 5. Many different permutation schemes are possible. For the case above, there are 24 distinguishable schemes. The case shown in Fig. 5 is easy to implement. The composite circuits may be kept separate, or linked at no more than one point, and may be driven by independent electrical supplies. However, such an arrangement is prone to instability due to the close mutual coupling between the various full circuits. Preferably, the various composite circuits are connected in parallel at both ends, but not elsewhere, making a single electrical entity or sub-entity, in which rapidly varying current is shared equally between the various composite circuits.

When a magnetic gradient is switched on or off, one preference is to avoid an uneven current distribution in the different composite circuits. Such an uneven distribution can be resolved into a set of equal external currents, plus combinations of internal circulating currents. When the magnetic gradient is switched on or off, the present invention preferably ensures that there is no net electromotive force (EMF) to induce such internal circulating currents.

Because of the detailed symmetry of the magnetic gradient, and of the magnetic fields it generates, when equal, positive current is driven through each of the composite circuits, magnetic flux of the same sign is linked through each spiral of each saddle. Thus, spirals A1, B1, C1, D1 all experience a respective flux $+\phi_1$ (etc.). In the present example, the total flux linking each composite circuit is $(\phi_1 + \phi_2 + \phi_3 + \phi_4)$. Hence, if two composite circuits are linked at either end to form a single circuit, e.g.(A1+B4+C2+D3)-(D4+C1+B3+A2), and the current in the magnetic gradient is changed suddenly, the net flux available to generate internal circulating currents is

$$(\delta\phi_1+\delta\phi_4+\delta\phi_2+\delta\phi_3)-(\delta\phi_4+\delta\phi_1+\delta\phi_3+\delta\phi_2)=0.$$

Hence there is no EMF available to induce uneven current distributions.

Taken over the entire structure, the composite circuits are electrically and magnetically equivalent. Current will exhibit no preference for one path over another, and at high frequencies more conductor will be active in carrying current, and the losses encountered will be less than in a conventional gradient design. Similar geometrical equivalence may hold for a Y gradient coil (say) in accordance with the present invention when the X or Z gradient is pulsed.

An equivalent interconnection scheme may be implemented with wire, rather than sheet, e.g. multiple, inter-wound circuits of electrically insulated wire. A single gradient axis winding may incorporate one or more such gradient windings connected in series, to constitute a whole gradient winding. Other variations are possible. In some cases a two-fold spiral implementation in which the sub-entity constitutes two saddles may be adequate.

The effective resistance of otherwise broadly comparable gradient coils has been measured as a function of frequency (Table 1 below). One gradient coil employs a limited track-width to control AC losses; the second, on the right of the table, employs the present invention. The slower proportionate increase in effective resistance with increasing frequency in the second case demonstrates the effectiveness of the invention.

Gradient	**Restricted track-width gradient (X axis)**	**Low-AC-loss gradient (X axis)**
Freq'	**R(mΩ)**	**R(mΩ)**
20Hz	~240 (estimated)	132
50Hz	~240 (estimated)	132
100Hz	245	134
200Hz	261	139
500Hz	357	168
1kHz	639	253
2kHz	1495	478
5kHz	5402	1213
10kHz	13713	3397

Table 1: Effective resistance as a function of frequency

The present invention includes equivalents and modifications within the scope of the claims of the present application.

CLAIMS:

1. Electromagnet apparatus for providing a magnetic field gradient, comprising first and second sets of conductors forming respective coil windings and each having the same plural number of conductors that are electrically isolated from one another within that set and are of different configurations, each conductor in each of the first and second conductor sets having a configuration which is matched by a corresponding configuration of a respective conductor in the other of the first and second conductor sets, the conductors of the first and second conductor sets beings interconnected such that each conductor in each of the first and second conductor sets is connected to a respective one of the conductors in the other of the first and second conductor sets having a configuration which does not correspond to the configuration of the conductor to which it is connected so as to form a respective conductive path incorporating the interconnected conductors, and the conductive paths being connected together to form the apparatus.

2. Apparatus according to claim 1, wherein said plurality of conductor sets comprises first and second said sets adapted and arranged for providing electromagnetic X field gradients.

3. Apparatus according to claim 1 or 2, wherein said plurality of conductor sets comprises first and second said sets adapted and arranged for providing electromagnetic Y field gradients.

4. Apparatus according to claim 1, 2 or 3, wherein said plurality of conductor sets comprises first and second said sets adapted and arranged for providing electromagnetic Z field gradients.

5. Apparatus according to any preceding claim, wherein said plurality is an even number.

6. Apparatus according to any preceding claim, wherein said conductors in said first conductor set are in a first configuration of interwound spiral conductors, and said conductors in said second conductor set are in a second configuration of interwound spiral conductors, such that the outermost conductor of said second configuration is connected to the innermost conductor of said first configuration, and the innermost conductor of said second configuration is connected to the outermost conductor of said first configuration.

7. Apparatus according to any preceding claim, including at least one further said first conductor set and at least one further said second conductor set, such that those further sets respectively constitute a third set of conductors and a fourth set of conductors, wherein said first and second conductor sets and said third and fourth conductor sets are at respective locations.

8. Apparatus according to claim 7, wherein said third and fourth conductor sets are displaced from said first and second conductor sets in a predetermined direction.

9. Apparatus according to any preceding claim, wherein said sets of conductors are adapted and arranged to provide a predetermined electromagnetic field in a predetermined space located relative to a nuclear magnetic resonance magnet.

10. Apparatus according to any preceding claim, wherein said first and second conductor sets are symmetrically disposed in space relative to one another.

11. Apparatus according to any preceding claim, wherein each conductor in each conductor set is matched by corresponding conductor of substantially identical configuration in the or each other conductor set.

12. Apparatus according to any preceding claim, wherein the conductors within each conductive path are connected in series.

13. Apparatus according to any preceding claim, wherein the conductive paths are connected in parallel.

14. Electromagnet apparatus substantially as hereinbefore described with reference to Figures 4 and 5 of the accompanying drawings.

15. A magnetic resonance imaging and spectroscopy system incorporating electromagnet apparatus according to any preceding claim.

Application No:	GB 9724743.1	**Examiner:**	Peter Emerson
Claims searched:	1-15	**Date of search:**	23 March 1999

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.Q): G1N NG38C, NG38

Int Cl (Ed.6): G01R 33/38, 33/385, 33/389

Other:

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X	GB 2315555 A	(BRUKER) - whole doc relevant.	1-5, 7-13
A	US 5311135 A	(GEC)	
A	US 5289129 A	(PENNSYLVANIA)	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.